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Too Little Too Soon? Modeling the Risks of Spiral Development

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Too Little Too Soon? Modeling the Risks of Spiral Development

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Abstract

The DoD's evolutionary acquisition policy is directed against project risk, but bears inherent risks of its own. The DoD policy for evolutionary acquisition mandates multiple product releases via spiral (i.e., amorphous & unplanned) or incremental (i.e., defined & deferred) development methodologies for all programs. All amorphous spirals eventually become definitive increments. Incremental development entails the deliberate deferral of work to a subsequent phase. Computational organizational modeling using systems dynamics reveals that this methodology introduces more concurrency during development, and more variety in production. The result is earlier delivery of the first increment, but with later and more costly

delivery of subsequent increments than if conducted via a single-step methodology. Curtailments of scope by the exclusive use of mature technology enable more effective delivery of the first increment, further illustrated by two case studies. Duplication, rework, transaction costs, decision backlog and error are causes of inefficiency in the successive increments. Production variety and mixed configurations produce obvious implications for logistical supportability, training, failure causality, compatibility and interoperability, etc. Further, certain attributes of hardware products might help determine the suitability of this development methodology. Products that are nearly immutable, which have binary requirements for key capabilities, require man-rating, or are maintenance-intensive may not be good candidates for incremental development. Mutable products with costless production, continuous requirements, low maintenance, or time criticality are more likely to reap advantages from this development approach. While modular open systems architecture facilitates system adaptation, modularity itself does not necessarily create evolutionary advantages due to relative modular interdependency. Program managers must be aware of the inherent risks of these agile acquisition methods and take additional steps to balance them with appropriate planning and resources, disciplined change-control measures, organizational accommodations and accountability for configuration management.

Keywords: Evolutionary acquisition, spiral development, incremental product development, Javelin, ATACMS, agile development methodologies, computational organizational modeling, modularity.

Introduction—The Inevitability of Change

We are told in Diogenes Laertius's *Lives and Opinions of Eminent Philosophers* (early 3rd century) that the Greek philosopher Heraclitus (c.535 - 475 BC) was the first to observe and say, “Everything flows; nothing stands still,”—the popular derivation of which is, “The only constant is change.” Indeed, everything does seem to change, evolve and give rise to variety in the world. Since his work in the 1830s, Charles Darwin receives much of the credit for furthering a theory of biological evolution. While not the first to have the idea, he associated observations of species *variety* on the island of Galapagos with species *environment*, and suggested that nature selected the variations that were the fittest (Darwin, 1859). In its time (and even since), the idea was considered radical and a threat to the religious and social order of things. Mere variety itself can be controversial, since, paradoxically, variety is appreciated in some domains (see the writings of William Cowper, 1731-1800)[1] and abhorred in others (Neave, 2000, March 2).[2] At the core of the subject of evolutionary acquisition are ideas and phenomena about variety and change. As a policy for system development, it is controversial too. As with Darwinian concepts, product evolution involves *information* transfer, interaction with the *environment* and unpredictability of change outcomes. But unlike evolutionary biology, product variations and selections occur frequently and are non-random. Program managers typically seek stability—in program requirements, in funding, in system design, and in production configuration. But it seems the only constant is change. Everything changes and

[1] See also: Kerr (1979, p. 65) about the basic human need for variety and complexity. Ashby’s Law of Requisite Variety states that the internal regulatory mechanisms of a system must be as diverse as its environment in order to cope with the variety of challenges imposed by it (Ashby, 1960).

[2] “Variation is nasty: it makes things difficult, unpredictable, untrustworthy: bad quality.” “In a big way, bad quality means too much variation, good quality means little variation.”

evolves over time. Much of what the authors have found in their following research on spiral development and project management is about how managers must cope with product variety and change. Using case study analyses, review of current subject literature, and computational modeling, the focus of our research was to ascertain the acquisition management implications of spiral development, obtain lessons learned in past programs as applicable to future development efforts, model and simulate projects using different acquisition approaches, derive predictions and make recommendations to project managers for the effective and efficient harnessing and implementation of spiral development.

Background

Projects have long been defined as *unique* and *temporary* enterprises, as opposed to common and ongoing operations. The latest (2004) version of the *Project Management Body of Knowledge* (*PMBOK*) increased its emphasis upon the term "*progressive elaboration*" to describe a third fundamental characteristic of all projects. It means, "developing in steps and continuing by increments; worked out with care and detail; developed thoroughly" (*PMBOK*, 2000; *PMBOK*, 2004, p. 6). This term relates to project uncertainty and describes the eventual realization of project scope only after multiple iterations of planning. The *PMBOK* asserts that progressive elaboration is both a necessary *characteristic* of projects (occurring throughout their lifecycles), as well as a *technique* for development of product specifications. It is accomplished via the learning that takes place over time as project ambiguity resolves, so that project scope becomes more explicit and detailed (as opposed to "requirements creep," which is considered uncontrolled change). The *PMBOK* later asserts that change in the course of projects and products is inevitable, and mandates the need for a *disciplined change-control process* to control its impacts—from inception to completion (*PMBOK*, 2004, p. 119).

There are many new DoD terms for project management and product development methods. DoD promulgated *evolutionary acquisition* (EA) as policy in 2000, and soon after, *spiral development* for the preferred acquisition strategy of all materiel. EA's goal is to phase requirements and provide capability sooner. But there has been confusion over terms, despite further elaboration and even codification in statute, and it still persists today, along with a lack of full understanding of many policy implications—especially some inherent risks. *EA operationally means there will always be multiple product releases of an item.*

The policy thrust is primarily about the reduction of product cycle-time within an uncertain environment, by exclusively using mature technology. The DoD's requirements process has also followed with "evolutionary" requirements documents—a new idea. Uncertainty is the usual realm of program managers, especially in defense systems, and is usually dealt with by seeking best information. Earlier reform initiatives were aimed at overcoming information gaps and technology lag. The 1990's Integrated Product and Process Development (IPPD) initiative was about gaining collective wisdom for early and complete requirements realization. As concerns over DoD acquisition program costs and cycle-times continue in the current mid-2000s era, the DoD has not abandoned the use of IPPD. But by embracing evolutionary requirements and acquisition, it has acknowledged that information will never be complete, either from stakeholders or with regard to ever-changing technology. It now implicitly concedes that developers will learn about their design over time ("requirements realization"), and users will accretively gain knowledge about how they can better use the new

capability ("product discovery").[3] Thus, a major paradigm shift for product development has occurred in the DoD: *from a collaborative quest to capture and address all requirements early on, to an allowance of eventual requirements discovery with full attainment only after visualization, feedback and environmental changes occur along the way*.

The Enabler: Mature Technology Reduces Risk

This is not to say, however, that the DoD has in its policy embraced technological uncertainty for the commencement of advanced development. Quite the contrary—for at the very heart of the evolutionary acquisition strategy is the requirement for the exclusive use of mature technology to reduce technology risk. The impetus for this undoubtedly lies in the body of work by the Government Accountability Office (GAO) over the last ten years,[4] which has obviously and greatly influenced the *DoD 5000* series. The GAO encourages the use of knowledge-based processes and specifically separates technology development from product development. It argues that shorter product cycle-times are the hallmark of program success and, therefore, should be limited to five years for more frequent introduction of new technologies into weapon systems, speeding them to the warfighter. We note that this is not much longer than the average development time for a new model of automobile—typically 3-4 years—which occurs in a very mature and cyclical industry (Kim, 2002, June). The GAO's target may ignore the significantly greater amount of technology development required in many DoD projects compared with most automobile development projects.

Most emphasized by the GAO (in the many reports reviewed by these authors) is the aspect of technology maturity before commencement of advanced development. The Office applies a 1-through-9 rating scale of *technology readiness levels* (TRL) that was developed by the National Aeronautics and Space Administration, adopted by Army and Air Force research laboratories, and recently implemented in the *DoD 5000* series (in particular, the *Defense Acquisition Guidebook*—formerly *DoD 5000.2R*). Until recently, the DoD had no specific requirements for use of TRLs, but levels 6 and 7 now satisfy its guidelines for technology maturity at Milestone B. TRL 6 states that the technology has been demonstrated in a *relevant* environment (simulating the key aspects of the operational environment), and TRL 7 is its demonstration in an *operational* environment (that which addresses all operational requirements and specifications required of the final system, to include platform/packaging). The GAO clearly prefers TRL 7 as the level of technology maturity that will represent a low and satisfactory risk for starting product development (GAO, 2005, November 15). The Office acknowledges that users may not initially receive the *ultimate* capability under this approach, but that the initial capability will arrive predictably *sooner and cheaper* (GAO, 2005, November 15).

In some respects, developing only mature technology as a fundamental program requirement is similar to an earlier attempt to constrain project scope. Cost as an Independent

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[3] The authors' terminology for what has so often been observed from their experiences. Most of us have long known that full realization of requirements and visualization of the product often takes multiple iterations of design, with feedback loops from modeling and testing activities. And sometimes the customer doesn't fully realize what can be done with the product until it is in hand. We call that *product discovery*, and the authors can cite several examples of this in both commercial and defense applications (i.e., cell phones as improvised explosive device triggers, etc.).

[4] See in particular: GAO/NSIAD-98-56; GAO/T-NSIAD-98-123; GAO/NSIAD-99-162; GAO/T-NSIAD-99-116; GAO/T-NSIAD-00-137; GAO-01-288; GAO-02-701; GAO-03-57; GAO-04-53.

Variable (CAIV) was an acquisition reform initiative that emerged in 1995 as a means of trading scope, or system performance, to achieve cost objectives. It was one of very few initiatives that were oriented on *what*, not *how* (i.e., processes) the DoD acquires its materiel.[5] To date, its actual savings benefit has been difficult to quantify, and qualitative measures have shown mixed results (RAND, 2005). Requirement attainment objectives and thresholds were another way to facilitate performance trades for cost.

When fully realized, *it is the exclusive use of mature technology in system development programs that is the key enabler of evolutionary acquisition* strategy, facilitating the rapid transformation of applied technology to end-item capability. Thus, it is the third of three principal observations, all of which are paradigm shifts, that we have recently observed: (1) that the DoD would now mandate program strategies for all programs to have multiple product releases of the same item, (2) that requirements would be deferred or allowed to evolve over time, and (3) that high levels of technological maturity would be requisite for commencement of advanced development, with an intended reduction of technical risk (and thus, project schedule) (USD(AT&L), 2003a, May 12, Enclosure—Additional Policy E1.14).

Policy and Implementation Concerns

But there are questions and concerns about these major shifts that several authors have raised. Still a relatively new policy, observations and realizations about the outcomes of evolutionary acquisition and spiral development are only just beginning to emerge, and will continue to surface until at least several major programs go through their entire lifecycle in this way. Sylvester and Ferrera (2003) provided some insight into the challenges and obstacles of evolutionary acquisition implementation—not from program-office level—but from the perspective of strategic policy-makers and subscribers at the Office of the Secretary of Defense (OSD)-level during their struggle to adopt the policy. In short, the authors explained the aforementioned confusion and ambiguity of the policy as it evolved from 1983 toward final promulgation in 2000, and then described the conflict areas caused by shifts in power among the organizational fiefdoms in the OSD and other affected institutions (i.e., Congress and the defense industry). In particular, they exposed the following major stakeholder communities and their respective *areas of concern* about evolutionary acquisition:

- Congress—loss of control over DoD programs via specific and informed authorization and approval; the inability to keep the DoD accountable; unknown implications of requirements and budget flexibility required for evolutionary acquisition.
- Military Departments—need to protect own acquisition programs and share of the DoD budget; retention of funding for follow-on capability increments; increased oversight; downstream logistics of multi-configuration products.
- Defense Industry—disruptions to commercial processes and traditional approaches to business; competition for follow-on increments; lower-rate production runs after shorter R&D efforts.

[5] Some may also assert that the moratorium against MILSPECS was similar in its thrust to reduce unnecessary work scope, but we believe specifications to be as much prescriptive (i.e., "how") as they are descriptive.

- Comptroller—controlling programs and holding them accountable; unknown implications of requirements and budget flexibility required for EA (program and budget "gaming" by services); "full funding" policy[6] versus open-ended requirements and fund streams.
- Requirements/Users—sub-optimum capability; priority of what is needed versus what is currently attainable; loss of follow-on increments.
- Test and Evaluation—loss of discipline and assurance of operational effectiveness & suitability; lack of comprehensive testing before several low-rate production configurations are released.

We have also had tactical (implementation) concerns about excessive decision bureaucracy (number of DAB reviews—see Figure 1), organizational challenges from multiple and concurrent development efforts, outdated technology at release, funds forecasting, transaction costs, and maintenance of subsequent increment priority. It is these phenomena that we have modeled with computational organizational design tools, which will be discussed later.

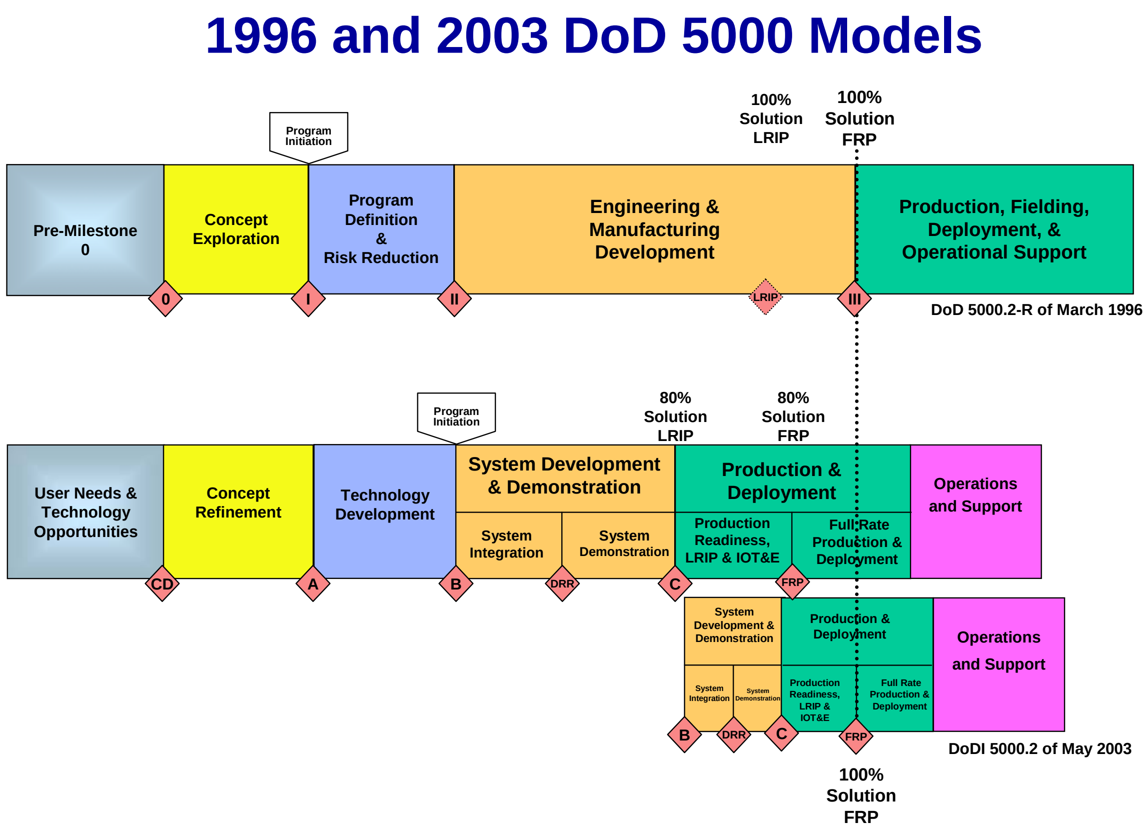

Figure 1. Comparison of 1996 and 2003 Acquisition Framework Models

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[6] The authors explain the dual meanings of this term later in this discussion.

The Costs and Benefits of Variety—and the Need for Control

Evolutionary acquisition methodologies, in addition to potentially adding more concurrency during development, increase variety in production. Both concurrency and variety are elements of complexity and program risk. Variety adds complexity in production and is costly for hardware owners and manufacturers alike. Traditional views about late design changes are negative, except for producibility enhancements and savings or correction of design flaws. But market consumers often need items in rapid cycle-times and appreciate product differentiation. In support of EA policy, the GAO has used product examples such as commercial vehicles. For the most part, we regard these commercial products as relatively "low-tech" on a comparative scale of DoD system complexity and capability. Moreover, we feel the GAO may ignore some very important aspects of ownership, since the DoD is unique as an outsourcer of capitol projects for internal use, and has unique requirements against competitive threats in combat environments.

Control measures are used to manage risk. One way of coping with the complexities of variety in ownership is via organizational and individual accountability. A recent example of successful control of rapid change lies in the Acoustic Rapid COTS Insertion/Advanced Processing Build (A-RCI/PB) program. In this vital program for sustainment of submarine acoustic sensing superiority, a series of hardware and software upgrades were planned and executed in rapid succession. Each emerged with advancement in capability, keeping pace with technology and competitive threats, facilitated by *rigorous control of interfaces, standards and protocols* (Boudreau, 2006).

Many other useful theorems on systems complexity, change and control exist that may be helpful for practitioners to consider, but are beyond the general scope of our research.

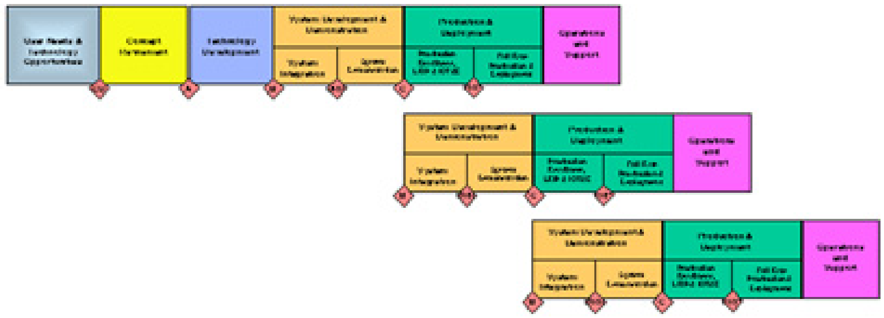
Do Product Attributes Affect Spiral Applicability and Outcomes?

Spiral development as a universal, "one-size-fits-all" strategy may not always be appropriate. Perhaps the foremost reservation is the appropriateness of the spiral development process for all project sizes and product commodities in toto, and the application of the spiral process to hardware products versus Boehm's original and most relevant application of this development approach toward software.[7] We speculate whether certain product characteristics might determine spiral development method applicability, and, thus, may offer important considerations for project planners.

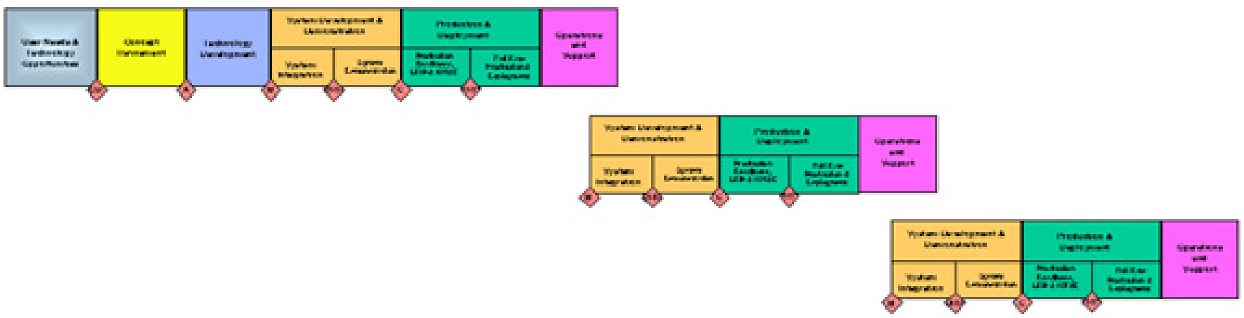
- <u>Mutability</u> simplifies change, and spiral development was conceived for the most malleable of products: "soft" ware, which is virtually costless in production. Multiple product increments do not often appear in large, *static, singular* projects such as bridges, highways, skyscrapers, or in other project areas that have *typically long lead times or product cycles*, such as feature-length films, pharmaceuticals, etc. These are what we call *nearly immutable* products and are much different than smaller projects (like small application software development) with much shorter development periods.

[7] And the authors will be quick to acknowledge that software is indeed a huge and growing part of hardware systems large and small. Still, the spiral development framework in current literature applies overwhelmingly to the realm of software, not hardware.

- Cycle-time and Phase Concurrency. Akin to relatively mutable or immutable products, we have observed the successive product upgrades visible in long-running aircraft programs (UH-60 Blackhawk and C-130 Hercules as examples) in which there are periods of production configuration stability, followed by improvement efforts, followed by another stable use period. Cycle-time for the development of each increment, and the relatively *successive* or *concurrent* phasing of the follow-on increments, will have a definite impact on program structure, budgeting, project complexity, and organizational issues, etc. For reasons that we will bring forth in our section on the computational modeling of spiral development, we have concerns about the conceptualization of spiral development programs with continuous and highly concurrent phasing of development increments. We suggest that, though concurrency is a necessary ingredient for efficient project management, it has also long been correlated with risk (because of activity interdependency), and might vary significantly with the types of activities underway (See Figure 2)—the inference being that periods of stable production configuration between development increments reduce complexity in program structure and attendant risks. Similarly, shorter cycle-times have less opportunity for knock-on effects or secondary consequences. Particularly in matrix organization structures, as often the case with projects, there can be a tendency to staff multiple projects with a single specialist. The more projects a specialist supports, the less they are *proportionately* available to the projects due to "queuing inefficiencies."Availability decreases because of the need for transition between projects (physical, mental, learning curve, etc.).
  - The end result has sometimes been shown to be large delays in project completion (Smith & Reinhartsen, 1998).
  - Similarly, Ibrahim (2005) has shown that discontinuous enterprise membership is a contributing factor toward knowledge loss in organizations involved in large, complex product development processes. Examining knowledge flows across product lifecycles, members often are not engaged in all phases. Whether from rotation of duties or multi-tasking, a discontinuous member's inaccurate knowledge could cause a functional error at the individual level which is not obvious at the enterprise's overall project level. These findings support observations of knowledge loss continuing despite investments in information technology and knowledge management.



Development Spirals/Increments Concurrent with Initial Production



Development Spirals/Increments Concurrent with Later Production

Figure 2. Concurrency Relative to Types of Activity

- <u>User Risk (Safety and Time Criticality)</u>. Time criticality and life-saving dependency, as opposed to user hazard levels (safety & man-rating), might seem to also have influence over design approaches. We have discussed above the area of technological risk and the DoD's use of incremental or spiral approaches to resolve it (along with a compulsory policy for the advanced development of only relatively mature technology). But DoD products have expanded risk considerations beyond Boehm's models of commercial software. Extending the idea of project risk-as-a-driver down to the level of the end-user, it might seem logical to assume that time criticality of the need or mission, where risk of not achieving project success actually endangers customer lives, might be a significant factor in the appropriate application of the spiral process for reduced initial product cycle-time. Perhaps defensive systems are a good example. The immediate needs for a Rocket-Propelled Grenade (RPG) defeater or an Improvised Explosive Device (IED) neutralizer for currently deployed forces in Iraq and Afghanistan, for example, clearly dictate that lives will be lost if a near-term capability is not achieved. We also cite as an example the National Missile Defense (NMD) initiative, in which, in view of near-term threats, early deployment of even rudimentary capability has been deemed preferable to waiting for full capability. Such urgency likely precludes full and certain requirements specificity.
    - Non-man-rated Systems: In an almost opposite vein, non-man-rated systems, such as Unmanned Aerial Vehicles or cave-exploring robots—capabilities in which operator lives are not at risk if the product fails—may also lend themselves readily to rapid innovation and risk-less experimentation cycles. However, user hazard levels for man-rated systems may be a different matter.

- Man-rated Systems: Configuration variety adds technical complexity with unpredictable interactions. In such projects as pharmaceuticals, aviation, vehicular transportation, etc., producers mitigate safety risks with thorough analyses, documentation reviews, testing and other control and verification processes. By their very nature—with lethal hazards for the end-user, and typically lengthy approval requirements—these may not be good candidates for a spiral approach. We believe this is why space experts say they'll not use spiral development with NASA's new Crew Exploration Vehicle (Roy, 2006).

- Production Quantity. As to product size or production quantity, we find no evidence that either precludes use of spiral—as with space vehicles and large ships—though support considerations do arise with variety that could greatly affect total costs of ownership.

- Logistical Support planned during Service/Shelf Life. Our observations warn that multiple configurations of hardware products do come at a cost for ownership. Veterans of new system deployments across the force/fleet, or throughout any large using organization, know the difficulties of rolling out a configuration change. Benefits of standardization have long been offered via production economies of scale, commonality of parts across platforms, and interoperability. If the ultimate goal is to have standardization across the DoD's force, owning multiple configurations of a system (variety) equates to added complexity in training and supply support of the item. Neither can the logistical maintenance strategy be ignored: whether the end-item is maintenance-intensive (such as tactical vehicles) or maintenance-free—such as with many electronics items and munitions, and situations in which physical changes are completely transparent to the user. For multiple product configurations, the answer could have a huge effect on the total costs of ownership, as shown by RAND on the proliferation of UAVs (Shaver & Amouzegar, 2005).

- Range of Requirement Attainment. Certain requirements are binary rather than continuous. Examples are soft launch, network security, physical fit, leak-proof, shock/vibration/drop proof, survivability, horizontal-to-vertical flight transition, etc. If one of these more binary-type requirements happens to be a key performance parameter, its attainment will be on the project's critical path and highly dependent upon technical maturity. As such, it may practically dictate the length of the entire advanced development effort and make division into capability increments less beneficial as a development strategy.

- Amount of Change—and the Lure of Modularity. These authors subscribe to the current theorists' view that system complexity is comprised of numbers (of components), connections (interdependencies) and distinctions (variety). Distinction corresponds to variety, to heterogeneity, and to the fact that different parts of complex systems behave differently (Heylighen, 1997). Variety is a component of Nobel Prize winner Herbert Simon's explanation of complexity—many different parts with many interactions. Simon argues, from his observation of complexity in things both natural and artificial, that complex systems evolve from simple systems. And they do so more rapidly when there are stable, intermediate forms or sub-systems (like modules or "units of action") (Simon, 1981). While the concept of modularity suggests approximately independent subsystems may be modified or adapted as such, it has been shown that, in the aggregate, there is yet quantifiable modular interdependency that affects evolvability (Watson & Pollack, 2005). In other words, how changes in the state of one module affect the state of another is relative and measurable. Thus, we suggest it is not only the focus upon structural modularity as such, and, standard interfaces, that enable systems evolution. Rather, it is the relative interdependency of the modules. In short, PMs need to be

mindful of the degree of change in subsequent spirals. One subsystem is likely to affect another in the short- or long-run. And that can make product evolution problematic. As Norman Augustine once said, “No change is a small change”; independent subsystems, even redundant ones, aren’t always independent (Augustine, 1997, June).

Development Case Studies

One of the most recent monographs we have found on emerging results of evolutionary acquisition is by RAND—on five immature, non-man-rated space systems. Space systems are somewhat different (in quantities, space environment, front-end investment, and extended technology development periods) than other DoD sytsems. RAND also found that policy confusion persists, and that EA added program complexity and uncertainty, especially with regard to budgeting. Extending their findings to non-space DoD programs, RAND highlighted the EA challenges of programmatic flux. They feel, and we agree, that EA presents the opportunity for typical PM challenges to be even more formidable.

Two missile programs were used as case studies for analysis and to illustrate planned and unplanned change. ATACMS used incremental and spiral strategies for product development. The program skipped its technology development phase by employing mature technologies for a leap-ahead capability in range. It arrived on budget and schedule, with several successive variants, pre-planned and unplanned. One instance of production change caused missile failure and costly refit of already produced missiles—underscoring the need for more thorough design specification and configuration management accountability.

Javelin used the single-step-to-full-capability approach to product development. The program embarked upon advanced development with immature technologies in several critical areas, causing significant cost and schedule overruns. It also has had subsequent design changes and product variety, more so as running production changes than as product variants.

Synthesis of these cases conveys that as an approach oriented primarily for reduction of product cycle-time, incremental or spiral development can successfully be used when developing mature technologies first. But a system’s physical properties like mutability, along with other factors such as time criticality (user risk) and modular interdependency, will drive spiral development applicability. And key capabilities may in fact depend upon the least mature technologies or even binary requirements. An “open,” or at least elegant, architecture is key to forming a basis for independent modular variety; and thorough design specification and configuration management accountability is essential for managing the complexity of multiple product releases. All amorphous spirals eventually become defined increments. Other well-known programs have used a spiral approach over their long product life spans, but often have successive phasing of their development increments.

Computational Modeling of Spiral Development

A computational experimentation approach to investigating evolutionary acquisition projects is explored below. This approach integrates theory and practice in a computational tool that allows controlled experimentation through simulation. The current work reflects project theory (e.g., the theory of constraints and work flows), product development theory (e.g., rework impacts and work dependencies), and management (e.g., resource management and information theory). Practice is reflected in the model through the use of case studies to build and validate the model structures (as described in the literature cited) and the calibration and testing using the acquisition projects described above. A computational experimentation

approach provides many advantages over pure and benefits from several of the strengths of both laboratory and field research. Nissen and Buettner (2004) describe and discuss the computational experimentation approach, and Dillard and Nissen (2007) describe its application to investigating acquisition projects.

The system dynamics methodology was applied. System dynamics uses a computational experimentation approach to understanding and improving dynamically complex systems. The system dynamics perspective focuses on the roles of accumulations and flows, feedback, and nonlinear relationships in managerial control. The methodology's ability to model many diverse system components (e.g., work, people, money), processes (e.g., design, technology development, quality assurance), and managerial decision-making and actions (e.g., forecasting, resource allocation) make it useful for investigating acquisition projects. Forrester (1961) develops the methodology's philosophy, and Sterman (2000) specifies the modeling process with examples and describes numerous applications.

Modeling Incremental Development with Multiple Development Blocks

Figure 3 depicts an acquisition project with multiple increments or blocks. Subsequent blocks have the same basic information flow, but can also be delayed by the completion of phases in previous blocks or constrained by the progress in their own blocks. Importantly, in addition to the flow of information downstream through phases (black arrows in Figure 3), multiple iteration acquisition also provides opportunities for information to flow upstream, such as from User Product Testing in an earlier iteration to Develop Requirements or Advanced Development in a subsequent iteration (red vertical arrows in Figure 3).

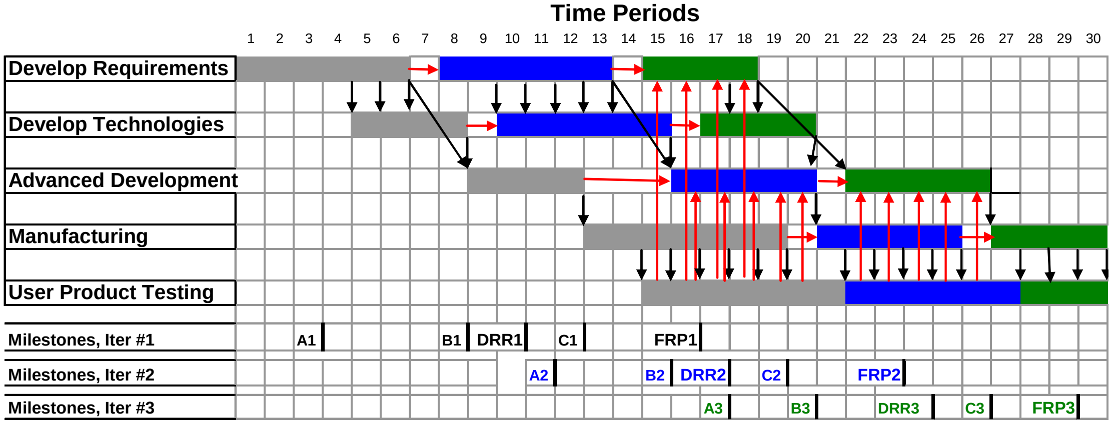


Figure 3. Information Flows in an Incremental Acquisition Project

In the model, the structure of each block is the same, although parameter values are varied to reflect different acquisition projects and strategies. For example, all phases include start-up work that is not directly applied to generating development products (requirements, technologies, component designs, or products). Each phase also includes the requisite review work that also does not directly generate product. This is consistent with GAO recommendations to manage each development block like an individual project. One impact of this loading of each phase with start-up and review work that we suspect has only been recognized informally is a significant increase in the total amount of work required to provide a given set of requirements to warfighters when multiple development blocks are used. As was

shown with our modeling results, this work has a significant impact on project performance that may impact the types of projects in which spiral development can be effective.

Computational modeling of incremental/spiral versus a single-step methodology yields results that illustrate our implementation concerns. Spiral development can provide the initial increment delivery with some (but not all) requirements satisfied earlier than in single-block development. However, spiral development takes more time and costs more to satisfy all requirements than single-block development. Spiral development has a high risk of not satisfying all requirements by the time single-block development can satisfy all requirements (See Table 1).

			Project Scenario		
		Units of Measure	**Javelin**	**Base Case - traditional**	**Base Case - spiral**
Performance Measure	**Duration to first requirement satisfied**	weeks	471	***470***	**397**
	Duration to max. requirements satisfied	weeks	520	**518**	***762***
	Total development cost	$1,000,000	722	**719**	***1,555***
	Requirements satisfied by deadline	%	**100**	91	***18***
	Final requirements satisfied	%	**100**	***91***	***91***

Table 1. Performance Comparison of Three Simulated Acquisition Projects

The causal paths that drive and constrain project performance in spiral development pass through multiple types of resources, development processes, and move across both development phases and development blocks. They also vary widely for different performance measures. This makes the drivers of and constraints on spiral acquisition project performance more difficult to identify than those in single-block development projects. Our modeling results indicate that spiral development is a significantly different approach to acquisition than single-block development, and requires different planning, resourcing, and management.

The concurrent use of multiple development blocks in spiral development significantly increases the number of development phases and activities that must be managed and coordinated at any given time compared to single-block development. This increases the project management needs for successful acquisition in spiral development projects compared to single-block projects.

As in single-block development, progress in spiral development requires the identification and understanding of progress bottlenecks. The concurrence and resulting complexity of development in spiral projects causes the types and locations of bottlenecks to vary widely and be more difficult to identify and address than in single-block development.

Causal paths of the drivers and constraints on project performance and progress bottlenecks move from one feature of a project to another as projects evolve. The increased dynamics of development in spiral development projects, as compared to single-block development, make identifying and addressing causal paths and progress bottlenecks more difficult. Progress bottlenecks can cause counterintuitive behavior, such as reductions in project cost, by adding resources at a bottleneck. Understanding and exploiting the opportunities provided by these behaviors requires a deep understanding of the project structures and dynamic interactions that drive and constrain progress.

Discussion—Recent Views on Balancing Risk and Control

Boehm's latest book on software development advocates balancing disciplined and agile methods to capitalize on the benefits of both. Discipline is needed as a control mechanism to avoid risk, but agility is needed to respond quickly to customer needs. Saying, "One size fits all is a myth"; he advocates a balanced approach based upon risk. He also advocates the more disciplined, risk-averse approaches for projects that are mission/safety critical, larger in size, and have more stable requirements (Boehm, 2004).

It could be summarized that spiral development was at its inception and is at its extension all about risk. Paradoxically, it is an agile method envisioned to reduce risk and, yet, can potentially add its own. On the one hand, a spiral or incremental approach allays risk by reducing scope to render only the highest priority capabilities with the exclusive use of mature technology, and obtains early and continuous feedback from the environment for follow-on developments. On the other hand, it introduces concurrency during advanced development and adds variety in production, with all their attendant management challenges.

Observations and Assessments

Although today's policy of evolutionary acquisition is prescribed as a development methodology, it is actually focused more upon what—not how—we develop. As such, it is about doable scope, reducing risk via exclusive use of mature technology. The Cost As an Independent Variable and other requirement-limiting initiatives were earlier attempts to accomplish this, by encouraging product performance trades to keep cost estimates fixed. As with CAIV, this likely means trading performance requirements for earliest-deploying increments.

Spiral development also seeks to spread out the technical risk over more development and process time via incrementing. We have shown with simulation that this can potentially improve risk management performance initially, but with higher overall costs and longer subsequent development durations, if deliberately deferring known, estimable work. As such, our computational modeling indicates that incremental development costs more and requires more time to provide the same requirements than single-step development. With regard to project risk, the increased complexity in a project using an incremental or spiral approach makes the isolation and effective management of progress bottlenecks more difficult than in single-step development.

The policy change is that spiral development now includes undefinitized increments and prescribes incremental development instead of single step development. All amorphous spirals will eventually become defined increments—mini-programs. In years past, they have often been implemented as sequential, separate, and successive product upgrades (such as the CH-47,

UH-60, C-130, B-52 program examples). But current policy expresses these as more concurrent, frequent and continuous. Such concurrency adds complexity to development models, with attendant risks of over allocation of work, noise, error, duplication, and other inefficiencies from work deferral and divided effort in project management organizations. Additional oversight, reviews, contracting, testing, etc., will also likely affect transaction costs. If all requirements are known and an incremental approach is used, then there is a deliberate deferral of work to later increments, and there will be a resultant increase in total development costs and durations for these same reasons.

Recommendations for Practice

1. Project managers need to be aware of the inherent risks of spiral development and take necessary precautions to balance those risks. Many tools and control measures are currently developed and available to assist project managers in balancing the risks of spiral development, such as technology readiness levels, configuration management, technology performance management, real options, project phasing, risk management, earned value management and organizational design.

2. Incremental and spiral development projects provide additional *opportunities* for managing development risk in the project design. These include project-planning decisions about the number of development blocks, the requirements and associated technologies and design components to be included in specific blocks. This planning provides opportunities to anticipate where critical progress bottlenecks may occur and design how to best monitor potential bottlenecks and respond to them.

3. Product attributes may help determine the suitability of spiral development as the best methodology. PMs may wish to consider such characteristics as: mutability, time criticality, man-rating, modular interdependency, key parameters of capability versus range of requirement attainment (i.e., binary vs continuous), and the relative amount of concurrency among increments.

4. Progress bottlenecks in iterative and spiral development often oscillate between process constraints (e.g., availability of work due to upstream progress) and resource constraints (developer or project management quantities or productivities). Successfully addressing a constraining progress bottleneck often shifts the limit on progress to a different location in the project. Therefore, a structured and interdisciplinary practice of identifying and addressing bottlenecks can improve performance.

5. Configuration management accountability must be assigned or kept to maintain supportability and failure-mode identification and causality and prevent the variety generated by spiral development from reducing total product performance.

Conclusions

We've suggested that a one-size-fits-all methodology for DoD system development may not be appropriate, and have offered for consideration several product attributes that might help determine the efficacy of the spiral approach. We further suggest that spiral development may serve better than single-step development for initial capability when products are mutable, time-critical, non-maintenance intensive, and have continuous (vs. binary) or uncertain requirements, short cycle-times (less knock-on effects), sequentially phased development, and modular

independence. In contrast, spiral development may not be appropriate when there are safety or man-rating concerns and have attributes opposite to those above. In particular, PMs should understand the nature of their product requirements with regard to their range of attainment and relative to key parameters of capability, and vis-à-vis the readiness level of their enabling technologies. Some key features may indeed be binary, and others may have significant ramifications of partial attainment—such as propagated change across the entire product componentry (as in weight reduction), versus a more independent, modular modification.

Open design standards will not always be incorporable. And product variety will emerge, with and without backward compatibility, interoperability, etc. Variety is both an asset (for end-users) and a liability (for manufacturers, owners and supporters). As such, to compensate for product variety, "owners" must "own" the design and emphasize configuration management, keeping or assigning responsibility for that function, and maintaining *accountability* for it.

Both *product specification*s as well as *risk realization* in spiral development move from being amorphous to defined. Spiral development has inherent challenges, both strategic and tactical, of which PMs must be aware. We've highlighted and illustrated them here, as well as showing (in our case studies) that spiral development can indeed work—especially for technically mature and mutable products with open or elegant architecture. Program Managers must be aware of these inherent risks, and take necessary precautions to balance them with increased use of tools, such as technology readiness levels, configuration management, technical performance measurement, contract incentives, options and phasing, organizational design, etc.

Stability is the quest in all things programmatic—for funding, requirements, design, configuration, etc. But in an unstable world, and with the future being necessarily uncertain, the tension between control and change is probably unending. PMs do have some tools for coping, and being forewarned is being forearmed. PMs are used to concurrency and change, as they are largely what make project management what it is—a balancing act. Mechanisms for control of risk include project management tools such as configuration management, technical performance measurement, earned value management, risk management, etc. Organizational and cultural factors such as leadership, trust and accountability play a significant role as well. Successful use of these tools to balance control and risk in projects with a high rate of change and concurrency is an area for our further study.

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Too Little Too Soon?

Modeling the Risks of Spiral Development

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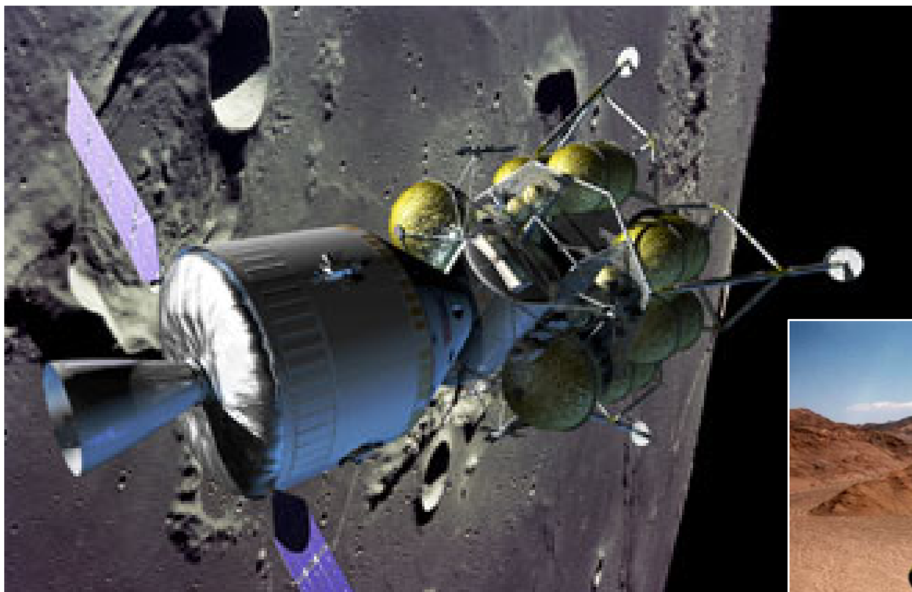
OPEN EVENT DETAIL

SPIRAL DEVELOPMENT, REAL OPTIONS, AND OTHER DEVELOPMENT METHODOLOGIES



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Report to Congressional Committees

March 2007

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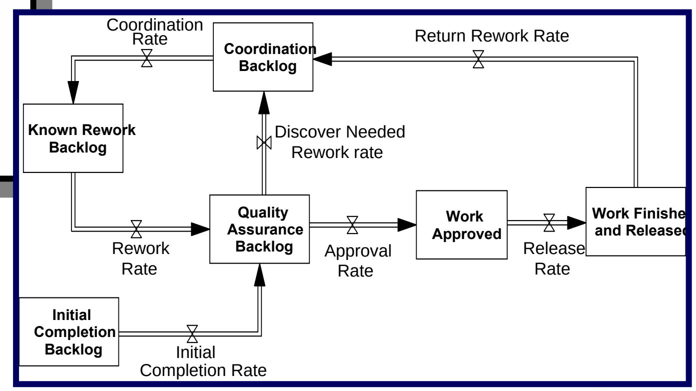
"Evolutionary Acquisition" Is a Promising Strategy, But Has Been Difficult to Implement

In 2003, the U.S. Department of Defense (DoD) specified evolutionary acquisition (EA) as the preferred approach to weapon system acquisition, and spiral development as the preferred means of implementation. EA strategies aim to develop new capabilities in multiple increments, as opposed to the traditional strategy of developing a full capability in a single, lengthier step. EA strategies are meant to reduce the time it takes to field operationally useful equipment, control technical risk and cost growth, and make cost estimates more reliable for each stage of development, while allowing greater flexibility to evaluate and improve a program based on experience in the field. This greater flexibility arises in part from the fact that, with the spiral development approach, the end-state requirements are not known at program initiation, but rather emerge and evolve through an iterative process of phased development and

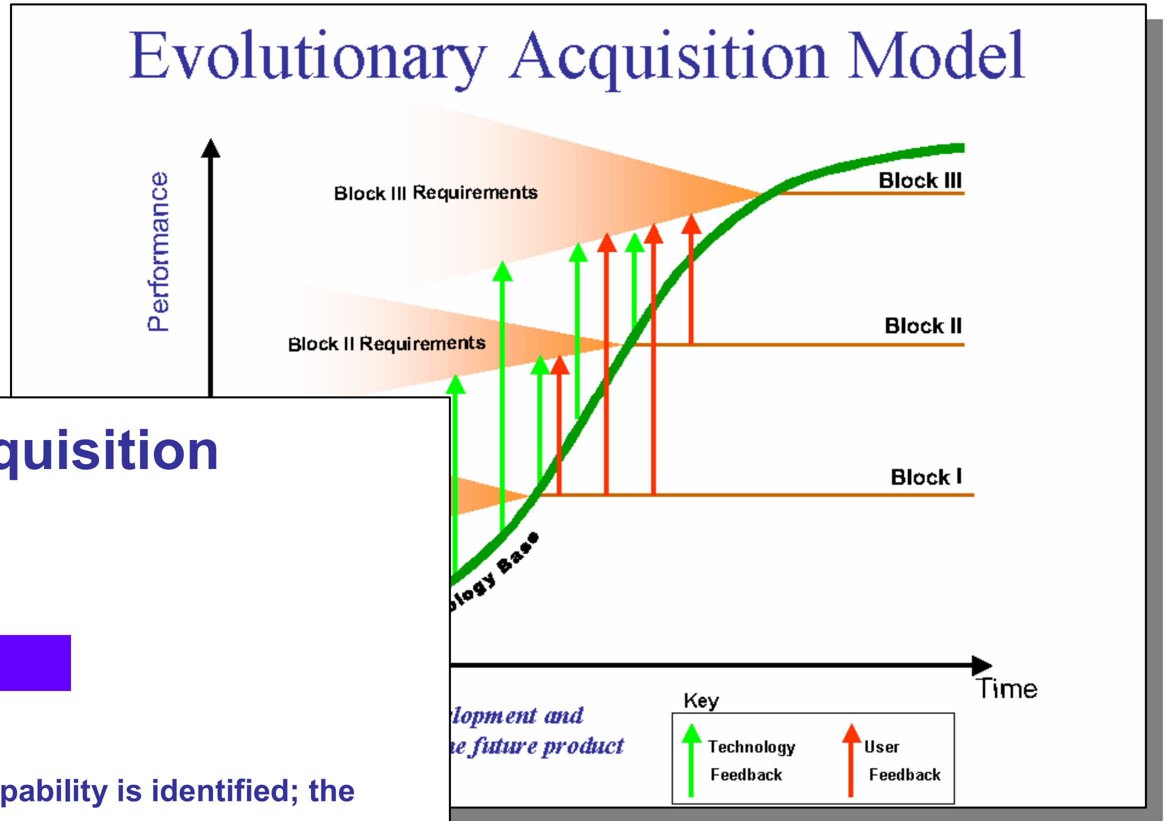
ATACMS

JAVELIN

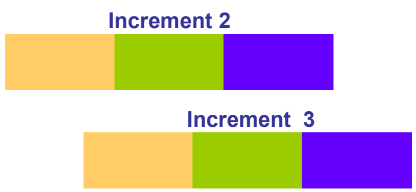


"Evolutionary acquisition strategies shall be preferred approach to satisfying operational needs."

DoDI 5000.2



Evolutionary Acquisition



Further defined:

- ***Incremental Development***: A desired capability is identified; the end-state requirement is ***known***; and that requirement is met over time by developing several increments, each dependent on available, mature technology.

- ***Spiral Development***: A desired capability is identified, but the end-state requirements are ***not known*** at program initiation. Requirements are refined through demonstration and risk management; there is continuous user feedback; and each increment provides the user the best possible capability.

5

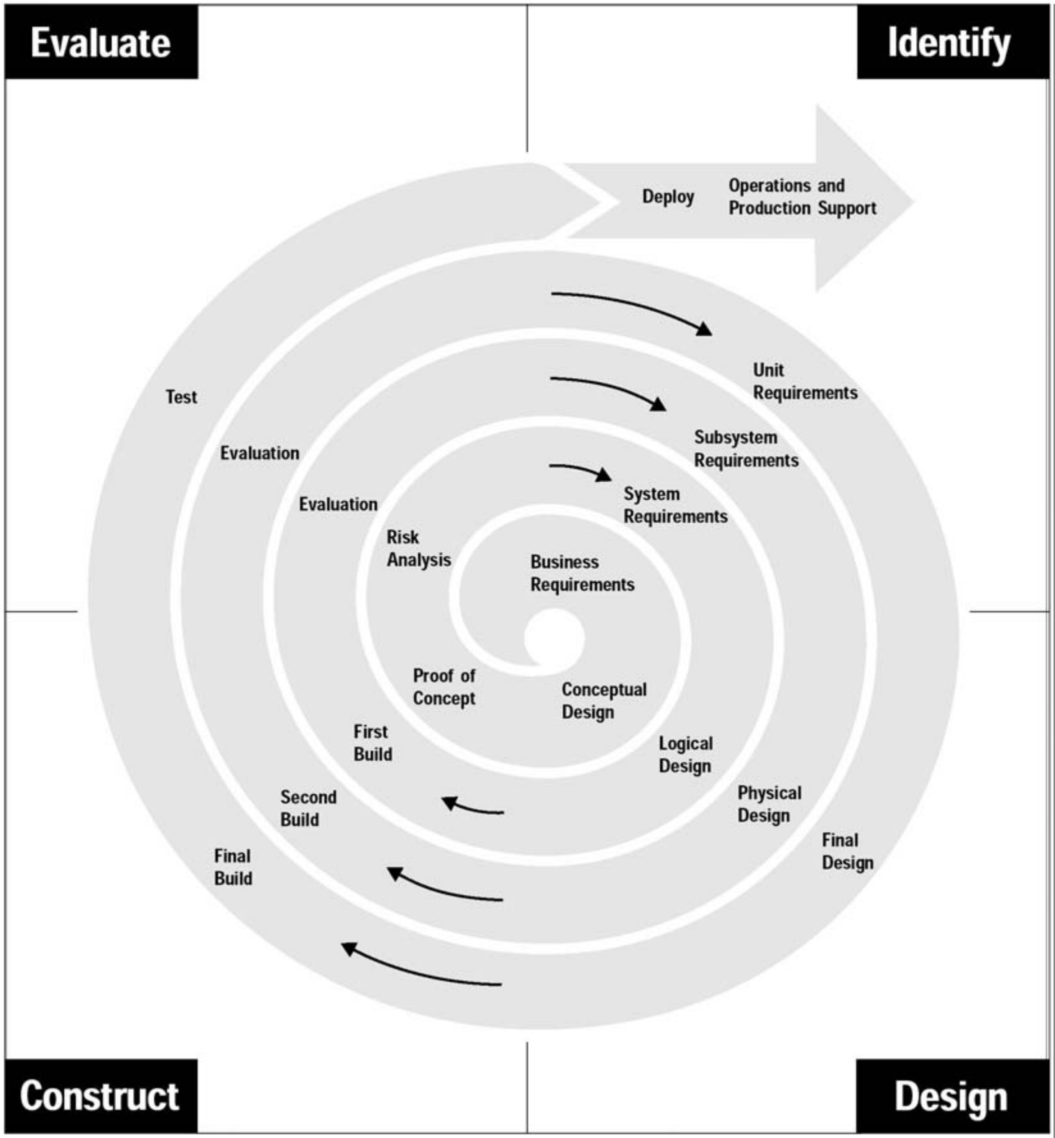
“Paradigms influence our study between revolutions” Kuhn

Paradigm

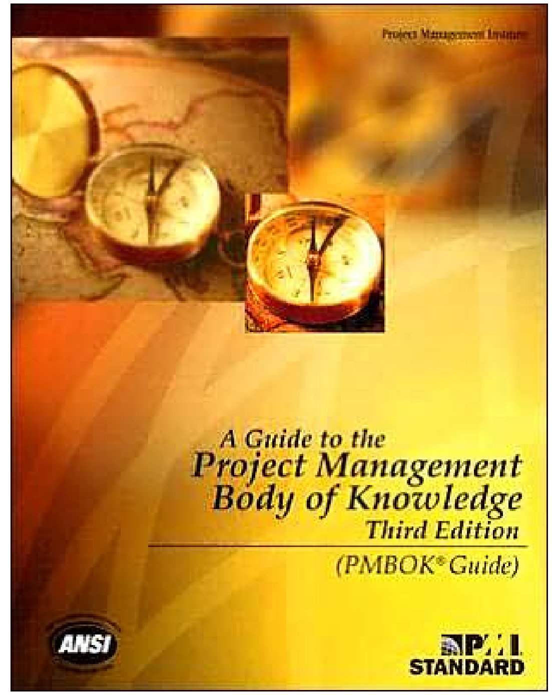
Paradigm

Paradigm

Barry Boehm’s Spiral Model of Software Development



PMI’s PMBOK:



“Progressive Elaboration”

Evolutionary Acquisition Issues

- Number of OSD-Level Reviews
  - Off-Core Activities
  - Significant Transaction Costs
- Unplanned work is inestimable.
- Fielding of obsolete technology -- if SDD isn't short
- Continued conceptual and definitional ambiguity (RAND)
- 1st increment: Militarily useful vs. all desired capabilities
- Organizational impacts of concurrent production and development of follow-on increments
- Maintaining of funding priority for follow-on increments
- GAO examples are mostly from cyclical commercial models, versus fleet ownership (i.e., United, UPS, Fedex)
- Variety brings benefits and costs

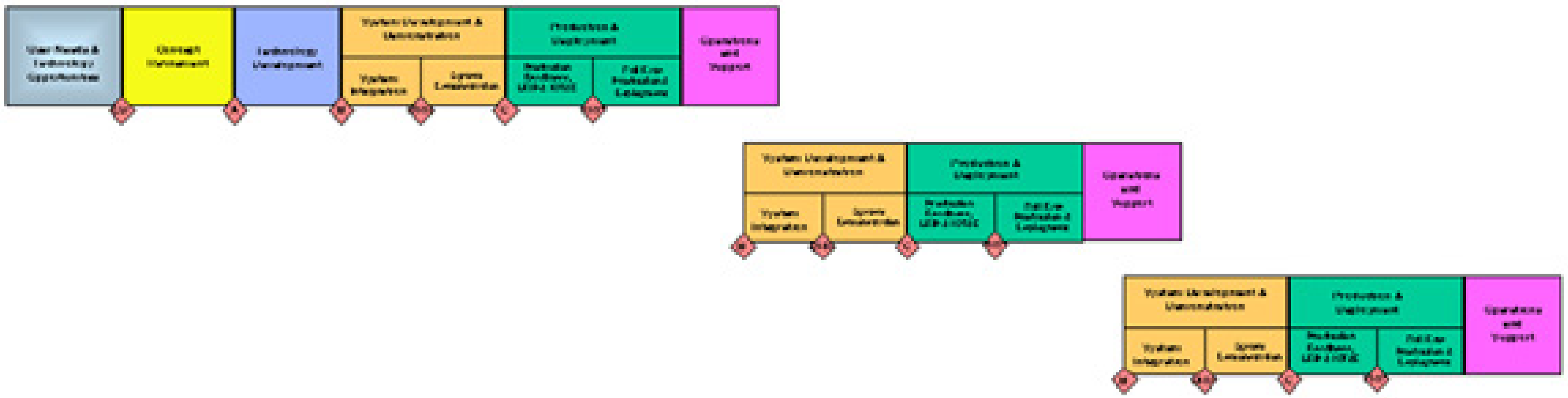
Everything Changes, But…

A *one-size-fits-all* development methodology may not be appropriate for all product commodities.

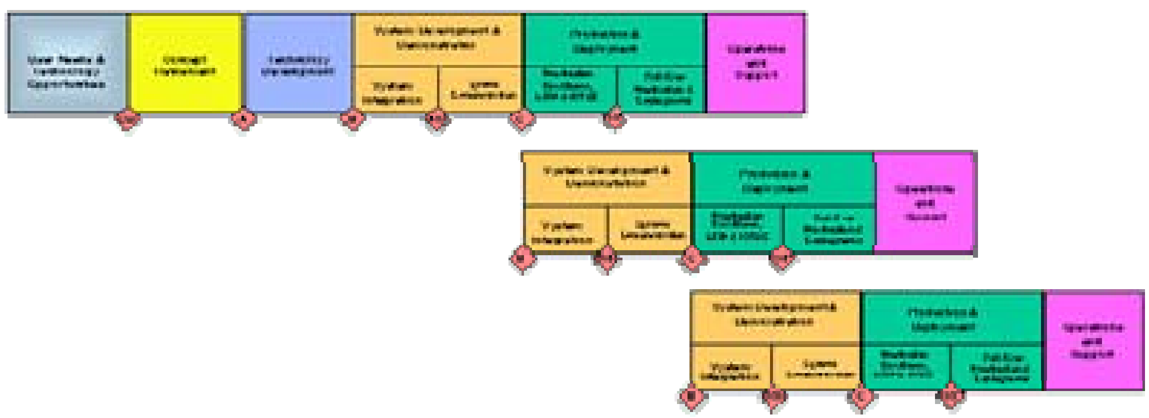
Product Attributes May Affect the Development Strategy

- Mutability
- Range of Requirement Attainment (Binary vs. Continuous)
- User Risk (Safety and Time Criticality)
  – Time-critical or enhanced survivability systems (NMD, ARCI)
  – Non-man-rated Systems (UAVs)
  – Man-rated Systems (munitions)
  – Production Quantity (not a factor)
- Logistical Support Planned During Service/Shelf Life
- Net Amount of Change - and the Lure of Modularity
  – Changes propagate with relative modular interdependency

Relative Concurrency of Increments



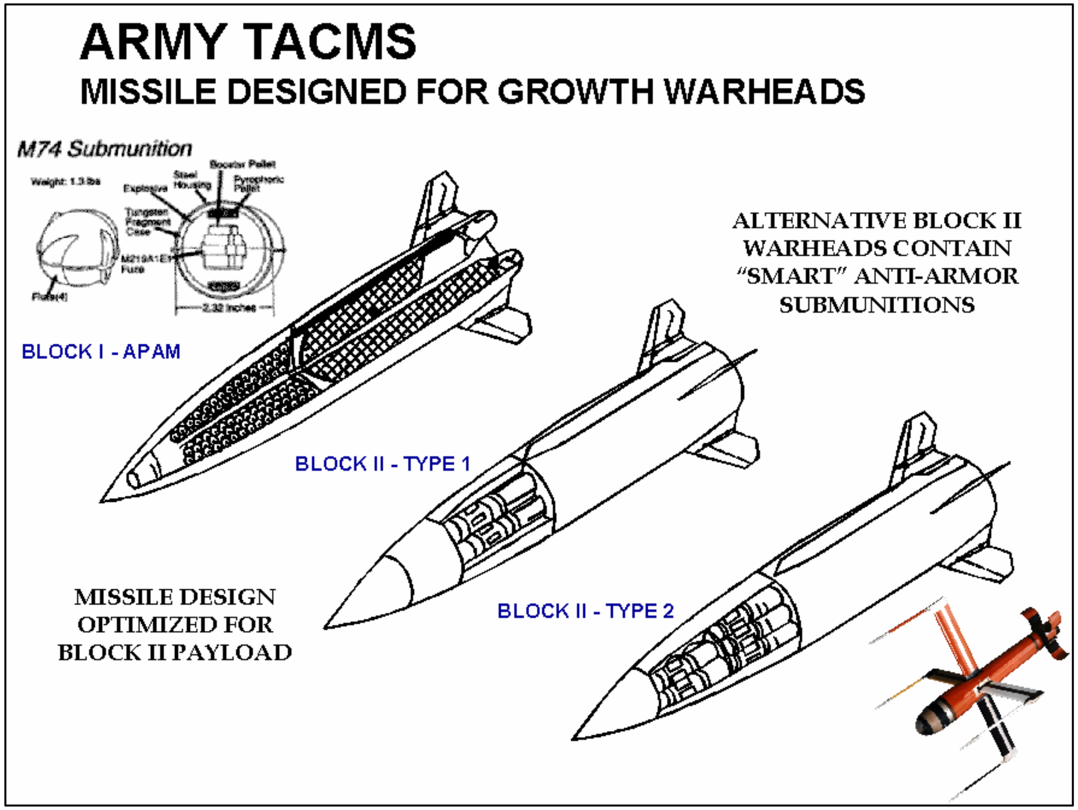
Development Increments Concurrent with Later Production



Development Increments Concurrent with Initial Production

A Tale of Two Missiles

Spiral and Incremental Development



Single Step to Full Capability

A Tale of Two Missiles:

Technology Maturity – A Key Difference

Key Program Characteristics - First Increment of Capability

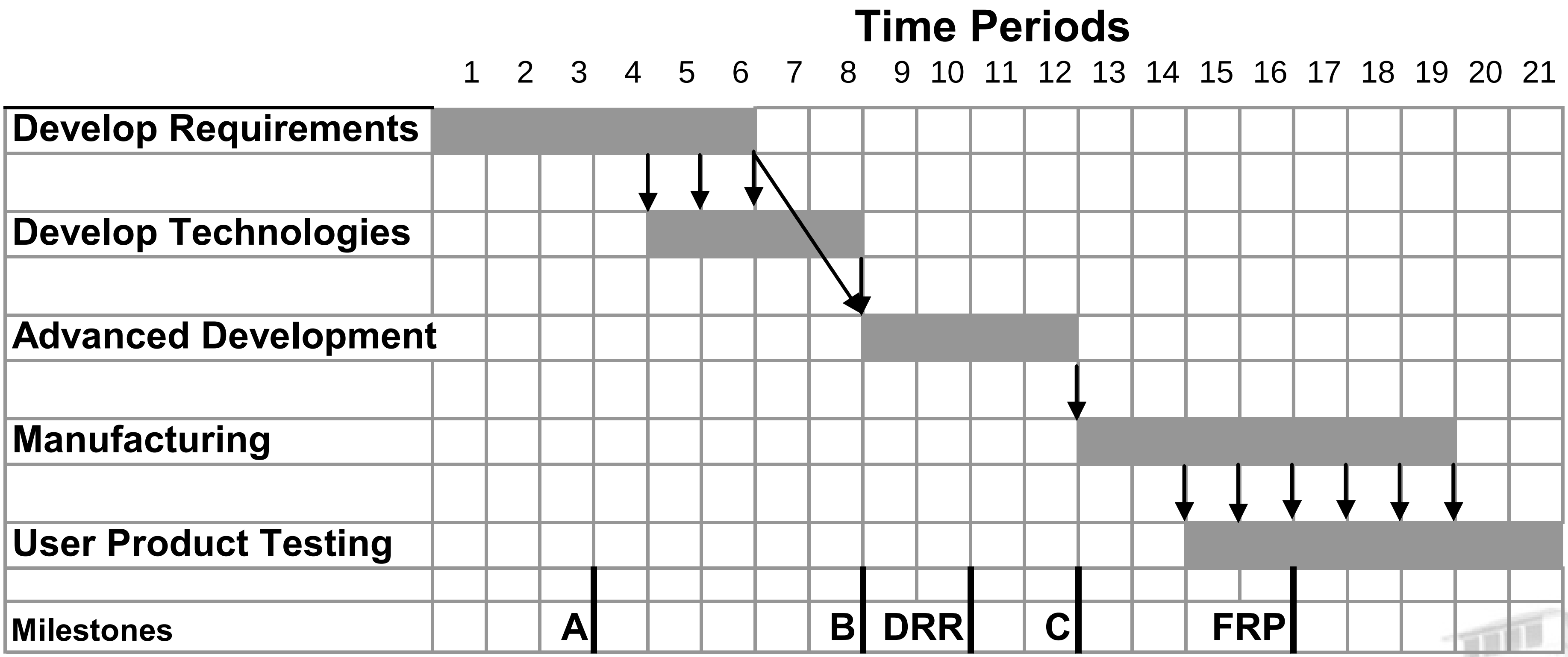
Program Aspects	ATACMS	JAVELIN
DARPA Predecessor	Assault Breaker 1977-82	Tank Breaker 1981-82
Ultimate Capability	*"Deep Attack"*	*"Fire & Forget"*
Critical Technologies & Readiness Levels:		
Munition	9 - Lance M74 Bomblet	5 - Tandem Shaped Charges
Propulsion	9 - Solid Rocket Motor	5 - Two-Stage Solid Rocket Motor
Flight Control	9 - Fin surfaces	6 - Fins + Thrust Vector Control Vanes
Guidance and Control	9 - Inertial	4 - Tracker Software Algorithm
Safe/Arm Fusing	7 - Mechanical	4 - Electronic
Software Function (Target Acquisition, Fire Control, etc.)	6 - Various	6 - Various
Sensor	N/A	5 – Focal Plane Array
Capability Leap Area	Range	Range, Lethality, Survivability
Cost of development	~$700M	~$700M
Contract Type	Fixed Price	Cost Reimbursable
Tech Development Phase	0 Months	27 Months
Advanced Development Phase - Planned	48 Months	36 Months
Advanced Development Phase - Actual	51 Months	54 Months
Total Time in Development	51 Months	81 Months
Advanced Development Phase Contract Cost Growth	0%	>150%

Modeling the Drivers and Impacts of Evolutionary Acquisition

- Need to validate the impacts of Evolutionary Acquisition suggested by the ATACMS and Javelin cases
- Need to identify other, less clearly visible, impacts of Evolutionary Acquisition
- Need to understand impacts using many strategies

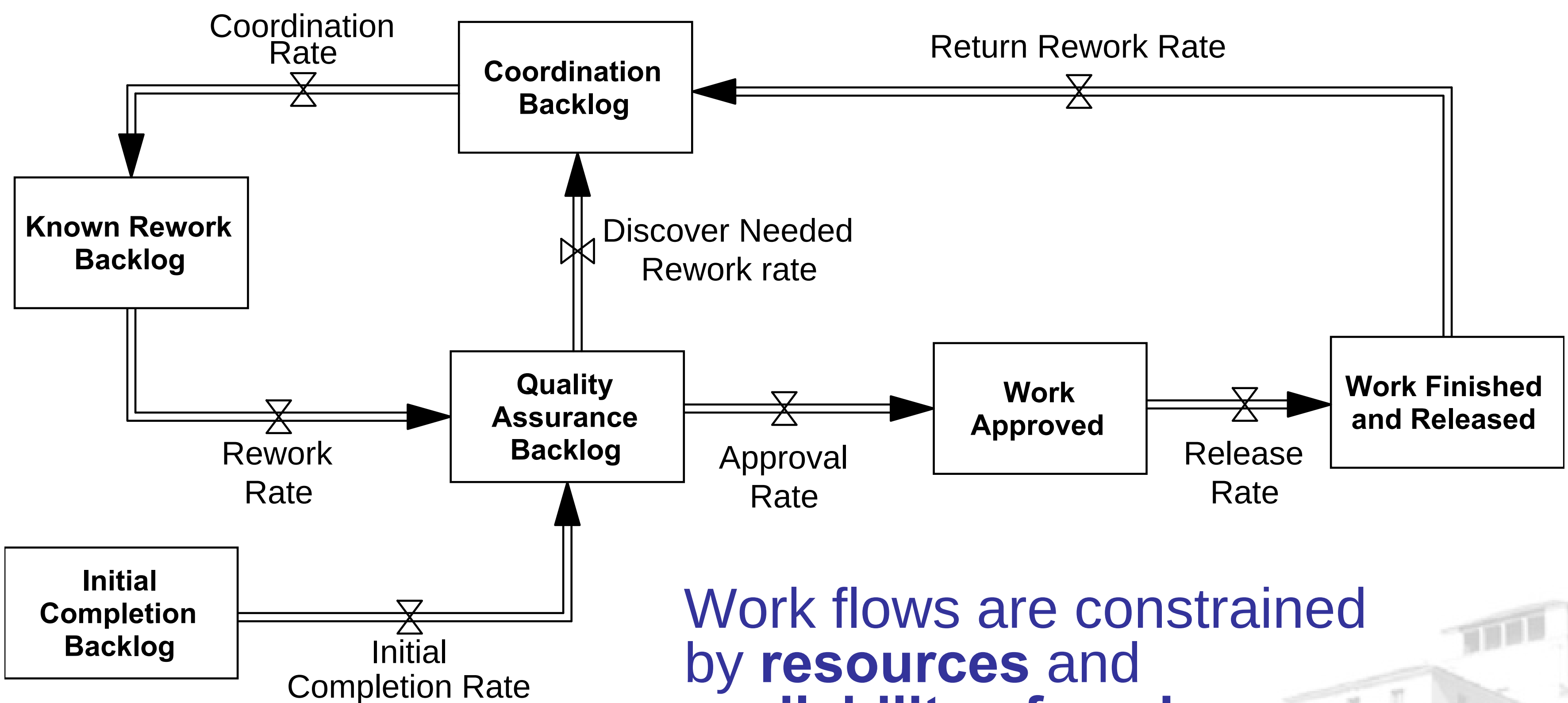
Built computer simulation model of work and information in an Evolutionary Acquisition project

Information Flows in a Single-block Acquisition Project



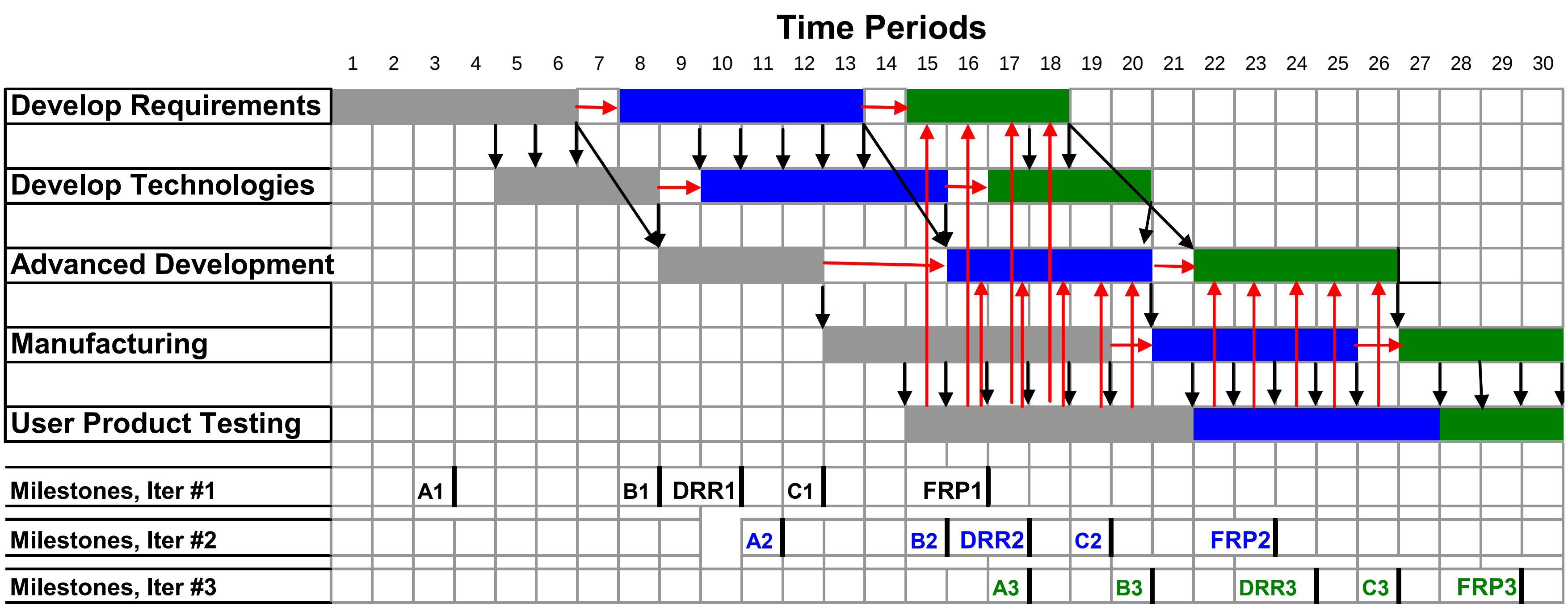
Models inter-phase concurrence & information dependencies

Work Flows and Backlogs through a Development Phase



Work flows are constrained by **resources** and **availability of work**

Information Flows in an Incremental Acquisition Project



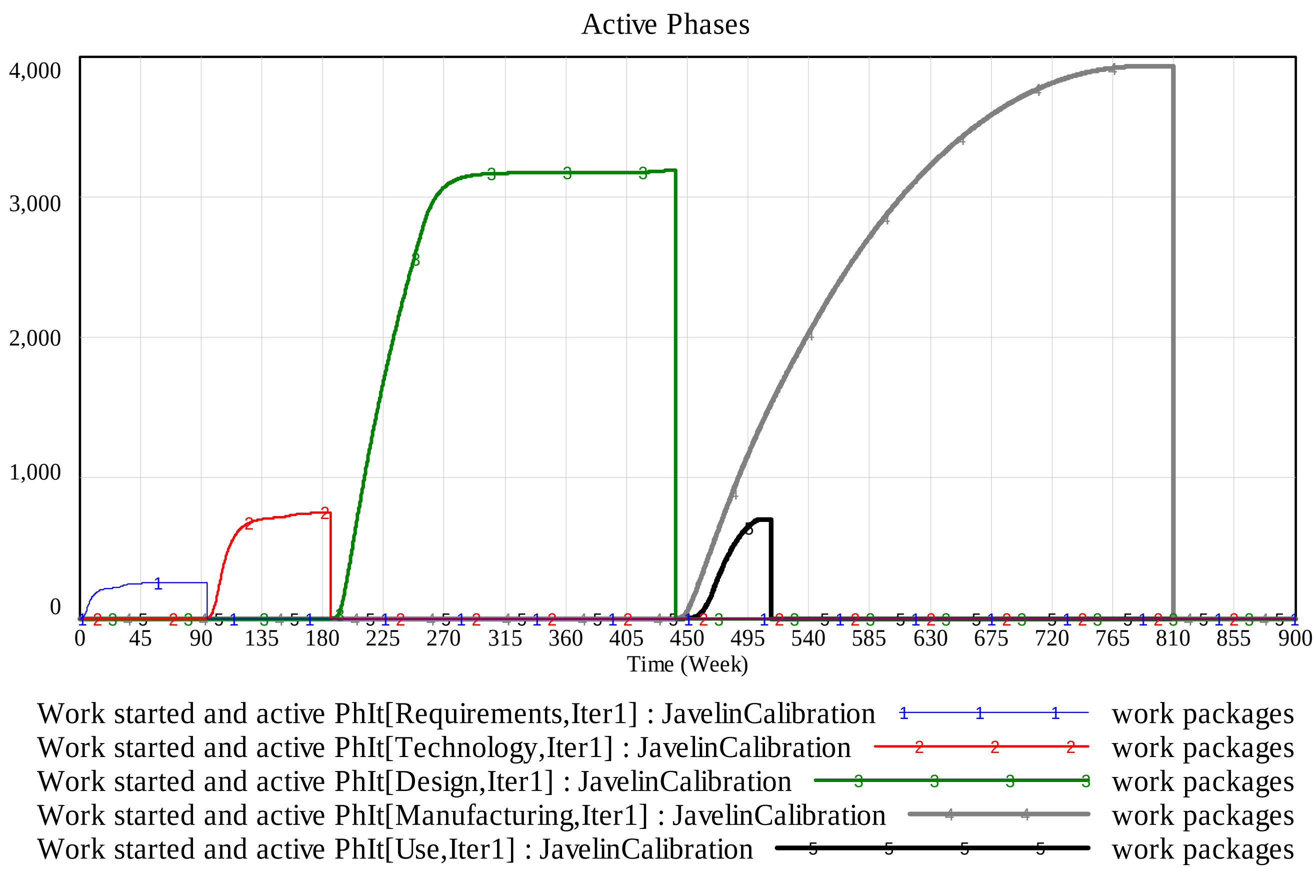
- Contracting, etc. modeled with indirect work at start of each phase
- Reviews modeled with indirect work at end of each phase

Modeling Performance and Resources

- **Acquisition Project Performance**
  - ***Schedule*** – when how many requirements are satisfied
  - Total project ***cost*** (labor as proxy)
  - ***Risk*** of satisfying requirements by a deadline
- **Resources**
  - *Two workforces*: Development & Project Management
  - Resource progress rate = allocated workforce * productivity
  - Development allocated to reduce work backlogs
  - Project management allocated to coordinate development activities

Model Calibration and Testing

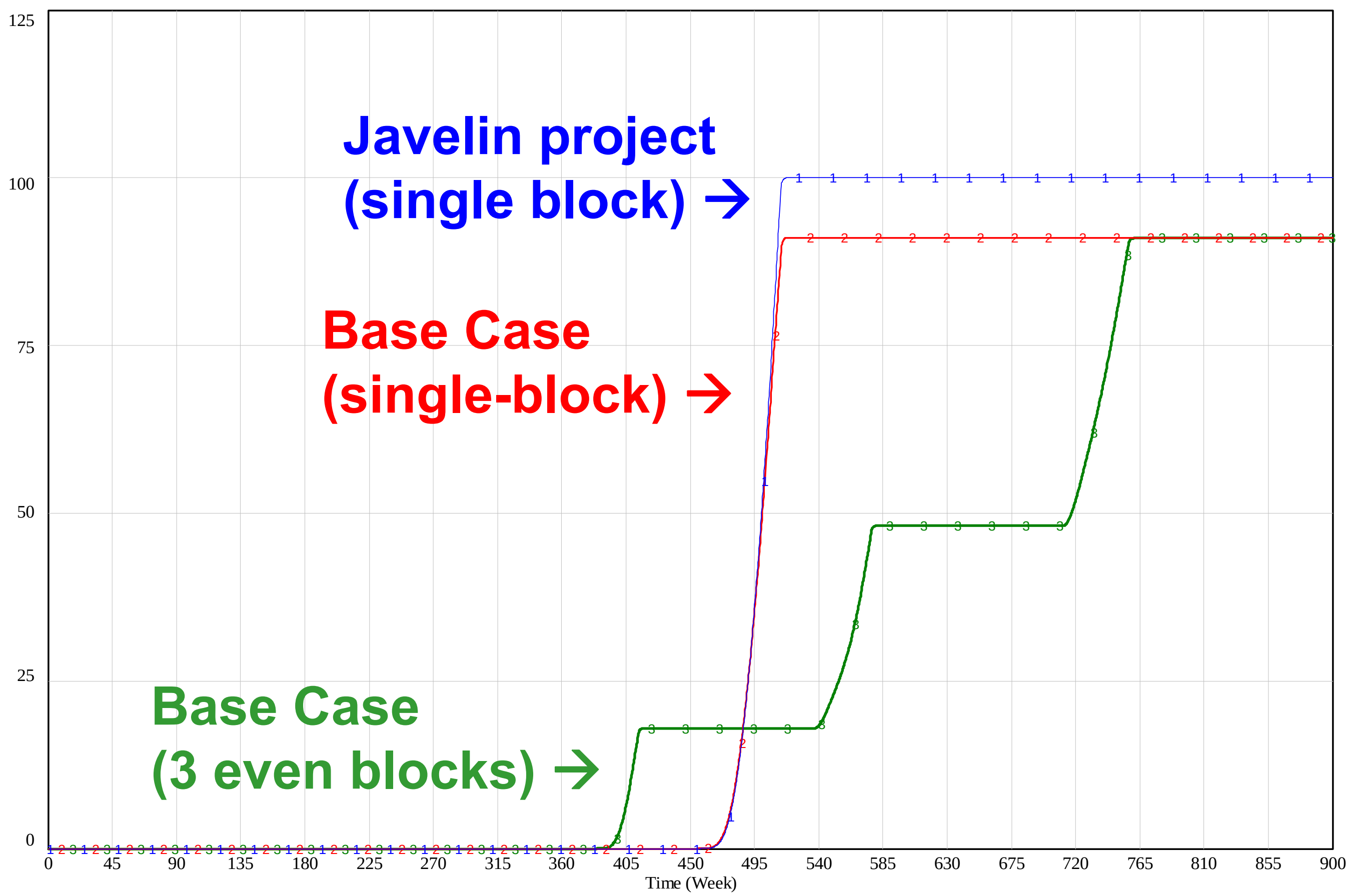
- **Model was calibrated to Javelin project**



Work packages being developed (also proxy for development effort)

- **Model structure and behavior is consistent with the Javelin project**

Impacts of Multiple Development Blocks



Requirements Tested and Approved by Users
(% of all project requirements)

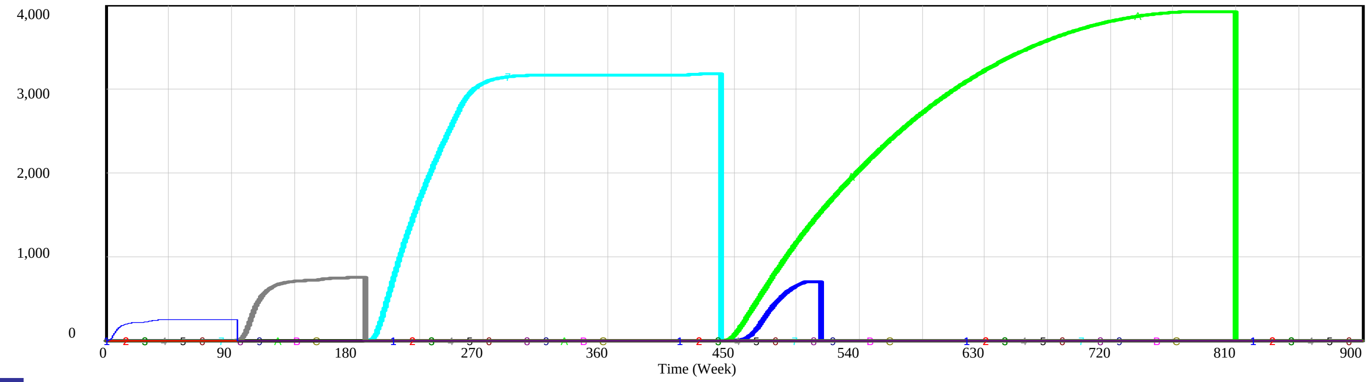
Impacts of Multiple Development Blocks

Performance Measure	Units of Measure	Project Scenario: Javelin (single block)	Base Case (single block)	Base Case (3 blocks)	Best Performance
Duration to first requirement satisfied	weeks	471	470	397	Base Case (3 blocks) ←
Duration to max. requirements satisfied	weeks	520	518	762	Base Case (single block)
Total development cost	$1,000,000	722	719	1,555	Base Case (single block)
Requirements satisfied by deadline	% of requirements developed	100	91	18	Javelin (single block)
Final requirements satisfied	% of requirements developed	100	91	91	Javelin (single block)

The (dis)advantages of Evolutionary Acquisition depend on what performance measures are most important.

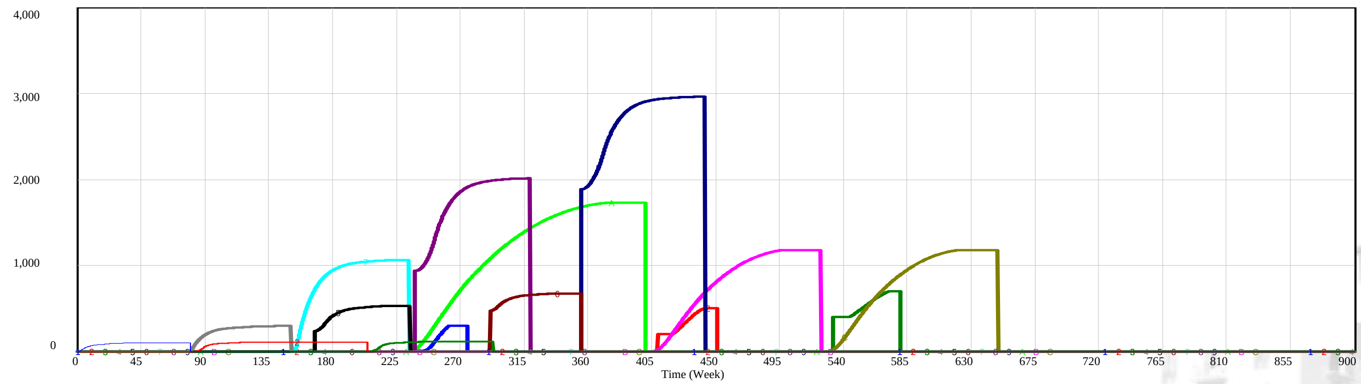
Managing Iterative Development

Base Case (single block)



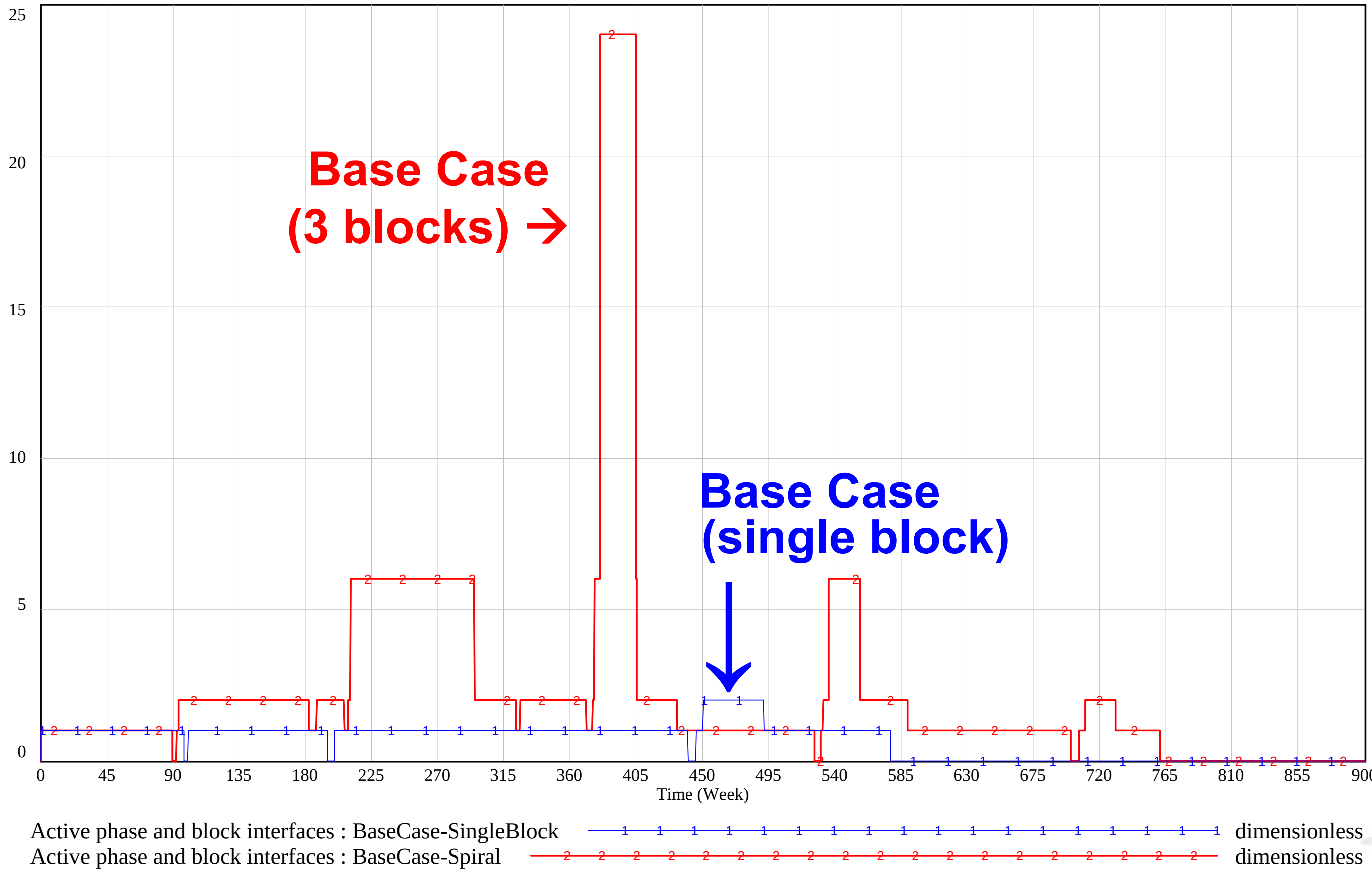
Work being Developed

Base Case (3 blocks)



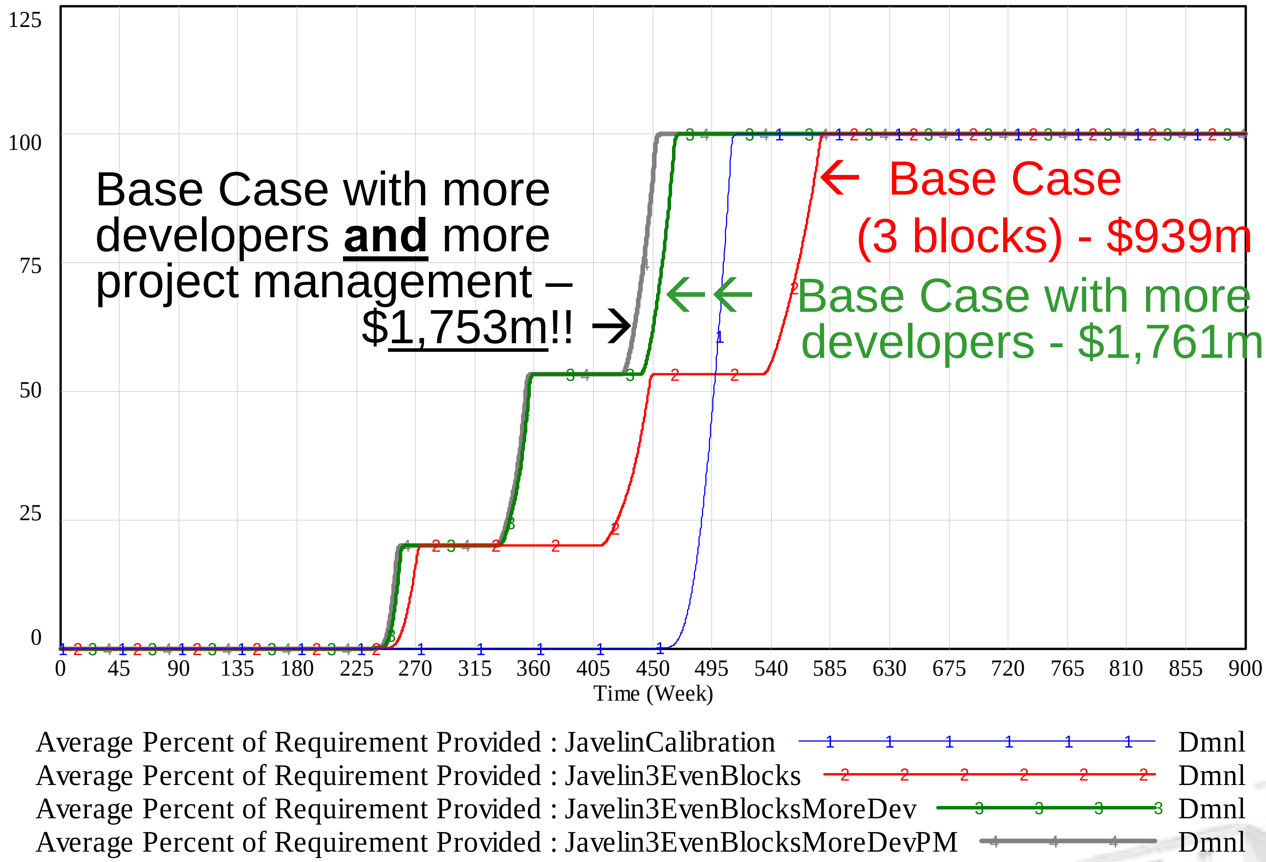
Managing Iterative Development

Number of Active Phase Interfaces



Managing Iterative Development

Requirements Tested and Approved by Users



Conclusions –Evolutionary vs. Single Block Development Approaches…

- First Unit Equipped with some (but not all) requirements satisfied ***faster***
- Satisfies requirements in ***multiple steps***
- Requires ***more time*** to satisfy all requirements
- ***Costs more*** than single-block development for same requirements
- High risk of not satisfying all requirements by the time single-block development can satisfy all requirements

Implications for Evolutionary Acquisition Project Managers

- More development phases and activities to manage and coordinate: ***larger and different PM needs***
- More concurrence and resulting complexity: ***bottlenecks change and move…are more difficult to identify and manage*** ← <u>focus more on this</u>
- Creates counterintuitive behavior (e.g.reductions in project cost by adding resources) – ***opportunities to improve performance…<u>IF</u> you develop a deep understanding of the drivers and constraints of Evolutionary Acquisition progress.***

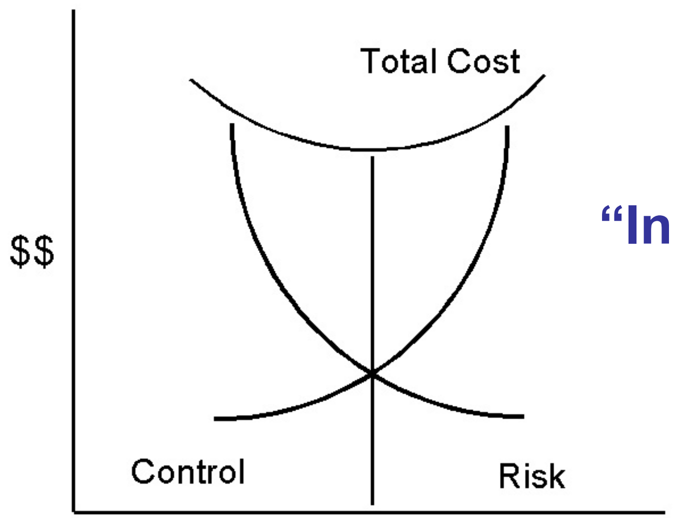
Need more investigation of more EA projects.

Our Bottom Line on Risks

- DoD uniquely outsources development for internal use
    - *owns* the product over its life cycle
- There are inherent potential risks with incremental development
    - inefficiencies from re-work (duplication)
    - risk of project error (from discontinuous membership)
    - organizational impacts (queuing theory)
    - relative concurrency drives risk
    - variety in the fleet (support, failure cause, training, etc.)
- Don't defer what you can do now
- Defer what you cannot do now – tech readiness
- Product attributes may affect development strategy

Our Top Line on Control

- Rigorous Preliminary Effort on ***Architecture***
- Meticulous ***Configuration Management***
- Individual ***Accountability***
- Other control measures to ***balance risks***
  - T&E, Interface Control, Peer Review
  - GPR, MOSA & OA Incentives, etc.



Perceived Relationships Among Project Cost, Control and Risk (adapted from Wysocki 2003)

"Intelligent design is way faster than evolution."

Robert N. Metcalfe

Questions?